Ultra-Thin Concrete Overlays on Existing Asphalt Pavement

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ABSTRACT

In 1991 an experimental project was built on a Louisville, Kentucky landfill access road. The purpose was to evaluate the feasibility of concrete whitetopping overlays less than 4 inches thick for residential streets, parking and other low-volume applications. The landfill site provided accelerated loading conditions and weight-monitored truck traffic data.

Two sections with different thicknesses were built, one 2 inches and the other 3.5 inches. The experiment also employed unconventional 6 foot and 2 foot joint patterns. These constituted the major variables of the test project.

The landfill traffic conditions necessitated "Fast Track" construction of the thin overlay experiment. The access road was only closed over one weekend and provided just a 41.5 hour window to complete the construction work.

This paper includes a description of the ultra-thin overlay performance. As of September 1992, both sections on the project are performing well and have carried over 585,000 Equivalent Single Axle Loads (ESAL's). The designs have out-lived predictions by conventional pavement theory and models. The authors will discuss the influence of the joint spacing and the overlay bonding on the bending stress conditions within the overlay slabs.

This paper will also document the design and construction of this project. The cooperation of all parties involved was a major factor and an outstanding tool for innovation.

The ultra-thin concrete whitetopping concept could induce major changes to the construction and resurfacing of asphalt roads, streets and parking areas throughout the United States. The promise shown by this initial experiment warrants further experimentation and discussion.

INTRODUCTION

An experiment being conducted by the Innovative Technology Committee of the American Concrete Pavement Association (ACPA), the Portland Cement Association (PCA), and other industry groups has found that concrete overlays as thin as 2 inches can perform well under typical loads for low volume roads, streets and parking lots. Whitetopping – overlaying asphalt pavements with concrete – is not a new technique. It is used successfully for many years to rehabilitate deteriorated asphalt pavements, airfields, and parking lots throughout the United States. But typically, whitetopping for pavements is at least 4 inches thick or greater.

PARTNERSHIP FORMS

In early 1990, the ACPA Innovative Technology Committee was debating the feasibility of thin concrete overlays. Concurrently, the Kentucky Ready Mixed Concrete Association (KRMCA) fostered two projects involving the placement of 3-1/2 inch pcc overlays on existing asphalt city streets. Having the same goal – to experiment further with ultra-thin concrete overlays in the field – members and staff of KRMCA and ACPA along with the Portland Cement Association formed a partnership to finance the construction and research of an experimental project.

KRMCA found an ideal road for the experiment that would allow accelerated overlay performance evaluation. The road, an access to a Louisville, Kentucky landfill, is traveled by over 600 trucks per day, 5-1/2 days per week. Although ultra-thin overlays are not intended for routes with this much truck traffic, the site provided an extremely accelerated simulation of 30 years or more of low-volume road, street, or parking lot traffic. Because all trucks entering the landfill are weighed, exact loading of the pavement was easily determined. The road is straight with a constant grade, and plenty of room alongside for equipment, all features good for the experiment.

A project advisory team was formed to design, build, and monitor the project. The team divided the whitetopping project into two 275 foot long sections. One section is 2 inches thick and the other 3-1/2 inches thick. Figure 1 shows the layout of the experimental project.

The access road could only be closed for whitetopping from 1:00 p.m. on Saturday until 6:30 a.m. the following Monday, which left only 41-1/2 hours to complete the overlays and ready them for traffic. The team decided to use fast-track paving techniques and a mix design that could achieve a 36 hour compressive strength of 3500 psi. Table 1 shows the mix design. A high-range water reducer helped produce a workable mix and high early strength. Polypropylene fibers were added for toughness and post-crack integrity.

WHITETOPPING PROCEDURES

The evening before concrete placement, crews milled the rutted asphalt surface. The milled surface provided a uniform plane and helped maintain uniform thicknesses along the overlay sections. Milling also left a rough surface that enhanced mechanical bonding between the asphalt and the concrete overlay.

Paving began at about 2:00 p.m. on Saturday, September 21, 1991. The day was sunny and the temperature was 78 degrees F. Concrete contractor, Harper Construction Co. Inc., Shelbyville, Tennessee, used a slipform paver to place the 24 foot wide roadway in one pass. Ready mixed concrete was delivered from a batch plant about 8 miles from the project site. The trucks deposited the concrete directly in front of the paver. The asphalt surface was lightly dampened before paving began to reduce absorption of the mix water into the asphalt. After overlay placement, the contractor sprayed on a white-pigmented curing compound.

Crews began joint sawing of the overlay at about 8:00 p.m. on Saturday with lightweight, diamond-bladed concrete saws. Most of the overlay was jointed in 6 × 6 foot panels. However, four interior panels in the 2 inch thick overlay section were sawed into 2 × 2 foot sections to evaluate a more "flexible" system. The theory behind the 2 × 2 foot panels was that loads would mostly be transferred directly to the underlying layers, acting like a typical flexible pavement system. In this area the concrete would act mainly as a stiff, non-rutting surface layer transferring load rather than absorbing it by slab bending.

Though doubts were raised about the constructability of the ultra-thin concrete overlay before the project began, paving proceeded without any problems. At 6:30 a.m. on Monday, September 23, heavy trucks began to ride on the overlay.

MONITORING OVERLAY PERFORMANCE

Law Engineering, Louisville, did all testing during overlay construction. Test results showed the concrete mix had a 2-3/4 inch slump, an air content of 6.5%, and placement temperature of 72 - 78 degrees F. Figure 2 shows average concrete strengths. The project committee selected the University of Louisville to do post-construction research and performance evaluation. This involved:

- Taking soil borings and asphalt pavement samples before overlay placement.
- Performing deflection testing before and after paving.
- Installing and monitoring strain gauges in the 2 and 3-1/2 inch sections.

In addition, staff engineers of PCA also conducted the following test:

- Concrete maturity and pulse-velocity testing immediately after placing and for the first 72 hours of pavement life.
- Recording the overlay internal temperatures after placement for the first 72 hours.

INITIAL FINDINGS

The performance of this experimental overlay has surprised not only the project advisory team, but many "nay-sayers" who did not believe the overlay could be placed. According to current pavement overlay theories, the experimental overlay (especially the 2 inch thick section) should have cracked soon after opening to traffic. The project advisory team believes the bond between the existing asphalt and the concrete overlay results in a significant drop in stresses in the concrete because the pavement reacts as a composite system. The construction success proved that concrete can be placed successfully as an ultra-thin overlay with conventional slipform equipment. The experiment also shows that concrete containing polypropylene fibers and high range water reducers are effective in Fast Track paving.

By mid September 1992, the overlay has been exposed to the continuous pounding of truck loads for one year. The estimated equivalent 18,000 pound axle loads (E-18's) the overlay has experienced is over 585,000, based on recorded traffic data. Table 2 shows a representative axle weight distribution for the project. It should be noted that the overlay was not meant to carry this level of traffic for twenty years. It was designed as an accelerated test to simulate many years of low-volume traffic. As a comparison, low volume roads, residential city streets, and parking lots typically are designed to carry only 50,000 to 100,000 E-18's over their entire 20-year design period.

After one year of service under this traffic level, the overlay is still in excellent serviceable condition. The 2 and 3-1/2 inch overlays have carried substantial loads without significant distress. The outbound lane, which carries unloaded trucks much more representative of low-volume traffic, has shown tremendous performance. Almost no slabs show visible signs of distress. Most remarkable has been the success of the 2 × 2 foot panels in the 2 inch overlay: even on the fully loaded inbound lane, not one of these panels has cracked or shown any other distress.

It should be noted that after about 400,000 E-18's, several panels of the overlay needed to be replaced. All replacements were on the inbound lane which carried fully-loaded trucks into the facility. The replacement area totalled between 50-60 feet of the total 550 feet experiment, or about 10% of the project.

The need for these replacements in these small areas was not caused by inadequate overlay thickness. One area was over a test pit which had been excavated as part of the experiment. The test pit backfill subsided under traffic loads. In another area the existing asphalt had been milled through to the granular layer. There was no existing asphalt present to bond with the overlay, and resulted in high stresses and non-uniform support. Finally, one section had very poor drainage conditions. The flowable fill shoulder had been built higher than the outside pavement edge and allowed standing water on the pavement.

The outbound lanes remain in almost perfect condition. It should be noted that during June, 1992, a third lane (8 inch PCC) was added to the access road to accommodate increased traffic. This new lane is now the outbound, or unloaded lane; the old outbound lane is now an inbound, or fully-loaded lane.

It appears that good bond between the concrete and existing asphalt, and very short joint spacing, seem to be keys to ultra-thin overlay success. The outbound lane which carries empty trucks is the most representative of low-volume traffic. The near-perfect condition of this lane proves the viability of ultra-thin overlays as a low-volume rehabilitation technique.

ANALYTICAL CONSIDERATIONS

Reports on the project by the University of Louisville (1) and the Portland Cement Association (2,3) have examined the project and experimental results in some detail. Field work, project distress monitoring, and analytical work were performed by the University of Louisville. Staff engineers with the Portland Cement Association conducted additional analytical modeling of the pavement sections to try and explain the phenomenal performance of the sections.

Significance of Bond

Mack, et al,(2) examined the theoretical stresses which are predicted for the experimental sections using a variety of models and scenarios. According to Westergaard's edge stress formulas, the maximum edge tensile stress at the bottom of the concrete in the test sections was 1183 psi and 2611 psi in the 3-1/2 inch and 2 inch sections respectively. This analysis assumes no bond between the concrete overlay and the existing asphalt. A modulus of subgrade reaction of 250 psi/in was assigned to the existing flexible pavement section.

Westergaard's formulas predict stresses well above the actual measured flexural strength of 1025 psi at 28 days (Figure 3). Since the pavement sections were not immediately cracking under truck loadings, Westergaard analysis does not represent ultra-thin overlay performance.

The finite element program ILLI-SLAB was also used to model the experimental sections. This program included the ability to model bond between the existing asphalt and the concrete overlay. Results showed a drastic reduction in edge tensile stresses when the concrete overlay was assumed to be bonded to the existing flexible pavement: 384 psi in the 2 inch overlay and 526 psi in the 3-1/2 inch overlay. Figure 3 shows the edge stresses between bonded and unbonded conditions. It is also interesting to note that the stresses are actually higher in the *thicker* section.

Analysis of finite element results showed that the bonding assumption creates a composite section. This effectively lowers the neutral axis and reduces the tensile stress at the bottom of the slab (Figure 4).

Mohsen, et al (3), conducted a fatigue analysis on the 3 1/2 inch and 2 inch overlay sections in their project report. The report states that all known fatigue analysis procedures used for designing pavements would predict that the 3-1/2 inch and 2 inch overlays would not survive the repeated loads on the sections. "The behavior of this composite concrete section, however, could be modeled using the fatigue curves for a 6 inch or even thicker concrete section."

The reports' calculations show that the behavior of the test sections are not of 2 inch or 3 1/2 inch slabs on a stabilized base. Rather, the pavement is definitely behaving as a composite pavement section with the concrete overlay bonded to the existing asphalt. As noted above, the theoretical tensile stresses in the two sections assuming bonding of the overlay were 384 psi in the 2 inch overlay and 526 psi in the 3 1/2 inch overlay. The strains actually measured in the overlay sections under similar loading conditions produced stress ranging from 360 to 420 psi in the 2 inch overlay and 120 to 160 psi in the 3 1/2 inch overlay.

In all test sections the magnitude of the compressive stresses at the top of the slab were higher than the tensile stresses at the bottom of the concrete. This seems to indicate the downward shift of the neutral axis in a bonded, composite pavement section. It should be noted that all of the strain gauges measuring pavement response were installed in the 6 × 6 foot panels.

A recent study by the Iowa Department of Transportation seems to corroborate these initial findings on the bonding of concrete overlays to existing asphalt (4). Grove, et al, studied the effect that different surface preparation techniques have on the mechanical bond which forms in whitetopping low-volume flexible pavements. Surface preparation techniques without a bonding agent included: brooming, brooming with air blasting, and milling. Techniques with bonding agents included: milling and brooming with a cement and water grout, and brooming with a tack emulsion. Study findings indicate that milling the existing asphalt produces the strongest bond at the overlay interface.

The study also concludes that no relationship exists between the bond strength and the contribution of the existing flexible pavement to the overall pavement strength. For all the examined surface preparation techniques, with the exception of those using cement and water grout, bond developed and the flexible pavement enhanced the overall strength of the pavement section. With this enhancement, the overall pavement strength is greater than predicted by conventional theory. Conventional theory assumes no bond between the pcc overlay and existing asphalt. The asphalt layer is assumed to act merely as a stabilized base.

Importance of Joint Spacing

When the experiment was originally conceived, the overview committee recognized that the thin overlay would require smaller joint spacing than conventional concrete pavement. This was the reasoning behind the overlay being sawed into 6 × 6 foot panels.

The committee also felt that the thin nature of the overlay may produce a behavior more similar to paver blocks than to conventional concrete pavement slabs. It was theorized that instead of responding in bending, the thin overlay section might be mostly in compression, transmitting wheel loads directly down to the underlying flexible pavement (Figure 5). To simulate this portion of the experiment, four 6 × 6 foot panels in the 2 inch overlay were sawed into 2 × 2 foot squares. These were interior panels in the section (two inside panels on both the inbound and outbound lanes).

Initial findings of the experiment seem to indicate that joint spacing in ultra-thin concrete overlays has a significant effect on overlay performance and traffic carrying capability. Although the 6 × 6 foot panels throughout the project are still extremely serviceable after over 500,000 E-18's, almost all of the panels on the inbound (fully loaded) lanes have low severity corner cracks at each corner. It is interesting to note that none have mid-panel cracks normally associated with fatigue failure There are very few cracks at all in the outbound (empty) lane.

Concurrently, one of the most remarkable results of the experiment has been the performance of the 2 × 2 foot squares in the fully loaded inbound lane. Not one crack or sign of distress is evident in any of these small panels - despite carrying almost 600 trucks per day for over a year. The 2 × 2 foot panels on the outbound lane are also completely intact.

An investigation of typical jointing parameters for conventional concrete pavements indicates one possible explanation which could explain the phenomenal performance of these small panels. Load and curl stresses in jointed concrete pavements are influenced by joint spacing. A dimensionless parameter, L/l, has been used to describe the relationship joint spacing can have to the overall structure of the slab. L is the joint spacing, in inches; l is the radius of relative stiffness, defined as follows:

$$l^4 = (E*h^3)/[12(1-u^2)*k]$$

where:
- E = the concrete modulus of elasticity, psi,
- h = the slab thickness, inches,
- u = the Poisson's ratio for the concrete, and
- k = the modulus of subgrade reaction, psi/inch

The radius of relative stiffness, l, has the dimension of length.

Ioannides, et al, have determined that for edge loading conditions, slab dimensions should be such that the L/l ratio is greater than 5.0 in order to obtain classic Westergaard slab responses for bending stress. When the L/l ratio is less than 5.0, bending stresses decrease and deflections increase. (5)

A calculation of the L/l ratio for the experimental sections indicates that the L/l ratio is about 4.6 for the 3 1/2 inch section and 7.0 for the 2 inch section for the 6 × 6 foot panels. However, for the 2 inch overlay cut into 2 x 2 foot squares, the L/l ratio drops to 2.3. Applying the theoretical effect a small L/l ratio has on reducing bending stresses in a slab begins to explain the tremendous performance of the 2 x 2 foot panels in the 2 inch overlay.

At some critical joint spacing and thickness, classic slab behavior (bending) is probably replaced mostly by deflection of the small slab - transmitting the load to the underlying layers in a manner similar to a flexible pavement. The performance difference between the 6 × 6 foot panels and the 2 × 2 foot panels in the 2 inch overlay indicates that the optimal joint spacing lies somewhere between these two sizes for 2 inch overlays.

Another recommendation for conventional concrete pavements is that the L/l ratio be between 4 to 6 in order to prevent cracking due to high curling stresses. The fact that the predominant distress in the fully loaded lanes is low-severity corner cracks seems to indicate that temperature and/or moisture curling could be lifting up the corners of the thin overlay panels. Poblete, et al, has conducted several studies (6) which indicate that pavements in Chile with conventional L/l ratios suffer primarily from this distress. This also conforms with performance of short jointed pavements in the U.S. The fact that the 2 × 2 foot panels have such a small L/l ratio that there is no curling may also help explain their outstanding behavior.

It should be noted that the above calculations of the radius of relative stiffness for the composite overlay sections, and therefore the L/l ratio, is not completely accurate. It is recognized that the classic definition of the radius of relative stiffness does not allow for a bonded condition or composite section. The actual radius of relative stiffness for a composite section would need to be derived from conventional slab-on-grade theory and is beyond the scope of this paper. However, it is strongly recommended that future research on ultra-thin overlays include a rigorous investigation of this parameter.

CONCLUSIONS

This experiment on ultra-thin concrete overlays of existing asphalt pavements has proven to be very successful and thought-provoking. Much has been learned, most notably:

- Ultra-thin overlays can successfully carry traffic levels typically associated with low-volume pavements, residential streets, and parking lots.
- Concrete overlays, as thin as two inches, can be successfully placed using conventional slipform paving equipment.
- Fast Track mixes minimize traffic disruption and are feasible with fibrillated polypropylene fibers and high range water reducers.
- Concrete overlays can bond to existing asphalt, significantly reducing stresses in the pcc layer. A substantial increase in structural capacity is gained as a result of this stress reduction.
- Only conventional rigid pavement models and theories which consider the effect of bond are adequate for describing the behavior and performance of ultra-thin pcc overlays on existing flexible pavements.

RECOMMENDATIONS

Although much has been learned by the experiment in Louisville, this paper, and the experiment itself, serves as more a point of departure rather than arrival; more questions have been raised than answered. Among the new questions are:

- What contribution does the bonding of the concrete overlay to the existing asphalt make to the overall pavement structure? It seems that this experiment, the study by the Iowa Department of Transportation, and years of performance of thin (5-6 inches) whitetopping projects all indicate that this contribution should be utilized in thickness design of concrete overlays on existing asphalt pavements.

- What is the fatigue life of this bond? Can its contribution be relied upon for large traffic volumes? Or, like aggregate interlock for load transfer, will it break down after a significant number of E-18's?
- Can this ultra-thin concrete overlay pavement section be modeled as a layered elastic system (as a flexible pavement) with a non-rutting surface layer? Can modeling the overlay in this manner lend itself to establishing a new design procedure?
- What is the effect of joint spacing on the performance of these thin overlays? The performance of the 2 × 2 foot sections definitely points to the fact that this parameter can have a remarkable effect on performance — even at higher E-18 levels. What aspects of the small panels contributes to their performance: ratio of slab size to thickness, ratio of slab size to loaded area, strength and/or fatigue life of the bond?
- Can the reduction or elimination of bending stresses in very small panels be characterized for use in pavements of all thicknesses? Would it be possible, for instance, to choose a pcc overlay thickness for clearance purposes, and then design a joint spacing which would adequately carry the design traffic?
- If very short joint spacing can eliminate bending stresses as a design consideration, than is high flexural strength of the concrete necessary? Or does the ultra-thin overlay only need to be strong enough to resist compressive forces from traffic?

It is clear that many questions need to be answered regarding ultra-thin concrete overlays on existing asphalt. It is equally clear that the experiment in Louisville, Kentucky, has opened new possibilities for the use of concrete as a pavement rehabilitation material.

ACKNOWLEDGEMENTS

This experiment was an outstanding example of the concrete industry working together to evaluate an innovative idea and to find an expanded use of resources. The project advisory team included professionals from ACPA, NRMCA, the Ohio Valley Chapter of ACPA, the Portland Cement Association, University of Louisville, and the Kentucky DOT. Also providing input were the ready mixed concrete producer, contractors, cement companies, public agencies, the admixture supplier, and the fiber manufacturer. More than 40 companies and industry groups gave financial support. The authors would like to thank all those who supported this important experiment and helped make it a reality.

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TABLE 1

ULTRA-THIN PCC OVERLAYS MIXTURE PROPORTIONS

Type I Cement	800 lb/cy
Course Aggregate (#8 Crushed Limestone)	1,799 lb/cy
Fine Aggregate (Natural Sand)	1,599 lb/cy
Air Content	4% - 6%
High Range Water Reducer (ASTM C-494, Type F)	14 oz./100 lb cement
Polypropylene Fibers (Graded, fibrillated)	3 lb/cy

The mixture obtained a laboratory strength of 4,000 psi in 18 hours.

TABLE 2

Axle Weights of Trucks on Pavement

(First Four Weeks)

Axle Load (Kips)	Number of Single Axles	Number of Tandem Axles
< 2	1,429	
2 - 4	888	
4 - 6	1,046	5
6 - 8	856	10
8 -10	577	35
10 - 12	730	27
12 - 14	1,007	59
14 - 16	1,418	43
16 - 18	1,245	165
18 - 20	892	51
20 - 22	539	87
22 - 24	353	183
24 - 26	205	254
26 - 28	215	345
28 - 30	158	516
30 - 32	61	638
32 - 34	51	615
34 - 36	68	582
36 - 38	70	539
38 - 40	60	449
40 - 42	25	356
42 - 44	17	319
44 - 46	21	309
46 - 48	4	249
48 - 50	2	195
50 - 52		97
52 - 54		75
54 - 56		83
56 - 58		69
58 - 60		40
60 - 62		9
62 - 64		3

Mix Design

Type 1 Cement	800 lb/CY
Coarse Aggregate (#8 crushed limestone)	1799 lb/CY
Fine Aggregate (Natural sand)	1599 lb/CY
Air Content	4%-6%
High Range Water Reducer (ASTM C-494, Type F)	14 oz/100lb cement
Polypropylene Fibers (Graded, fibrillated)	3 lb/CY

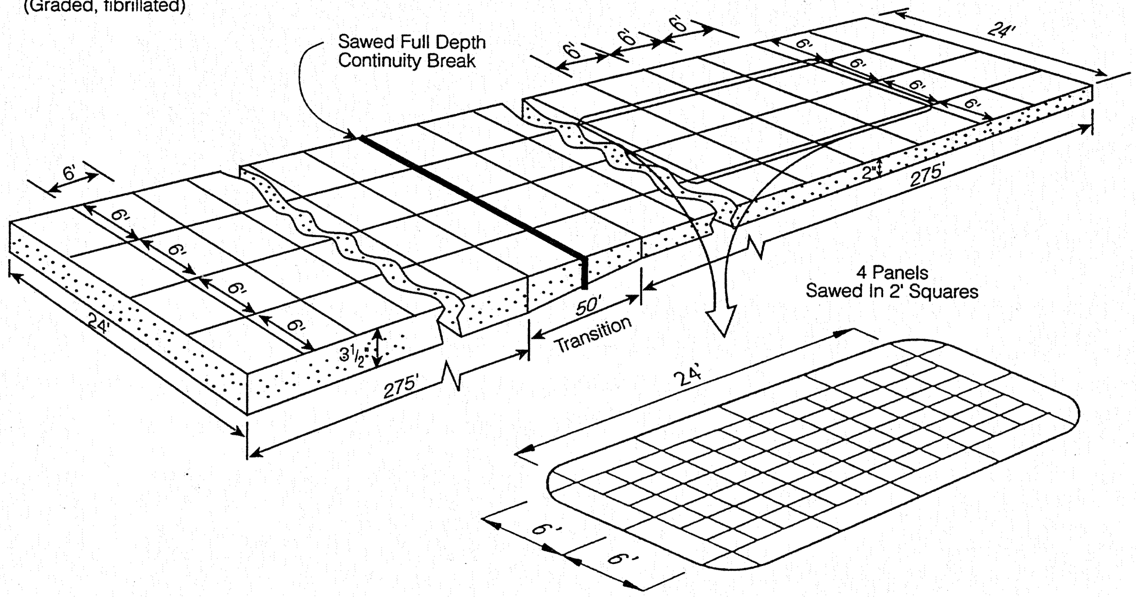

Figure 1

CONCRETE STRENGTHS

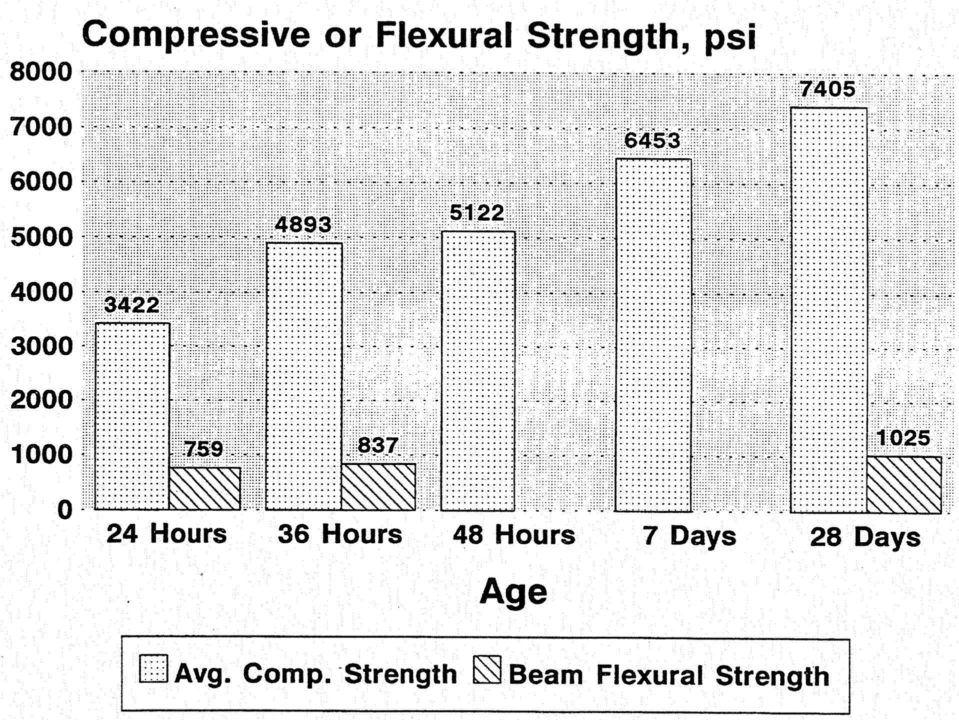

Figure 2

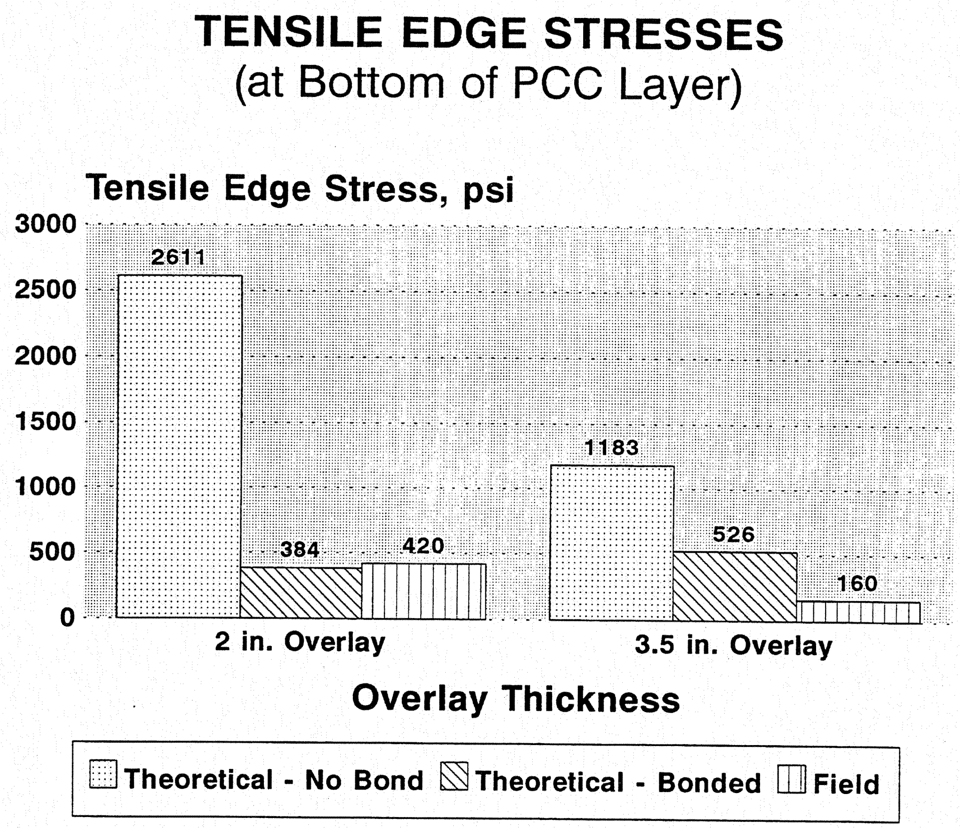

Figure 3

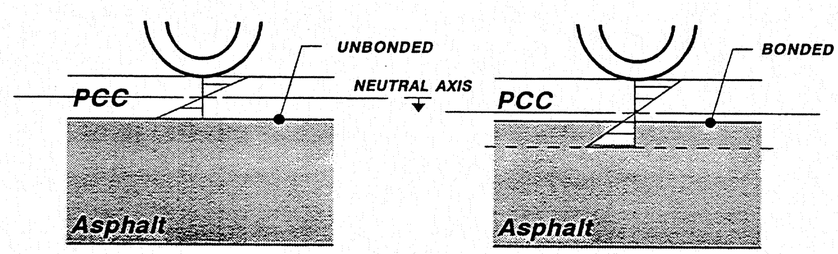

Figure 4: Lowering of neutral axis in composite section.

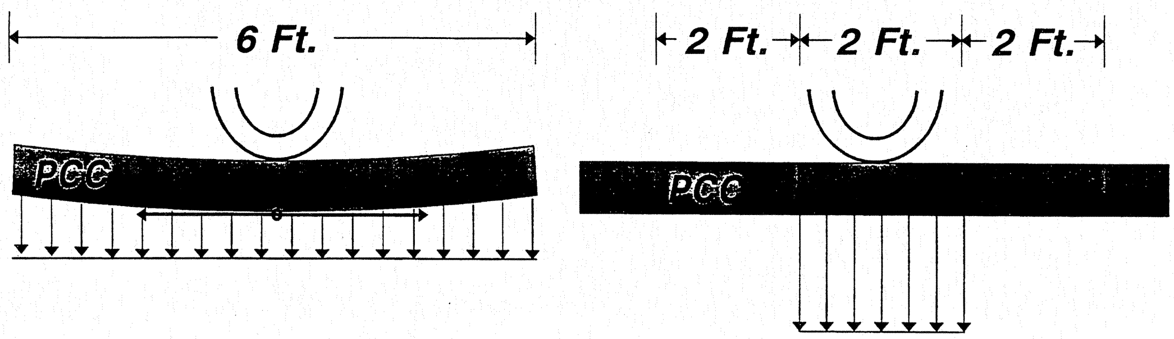

Figure 5: Very Short Joint Spacing May Greatly Reduce Bending Stresses in Thin Overlay Slabs